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# PV in Historic Dwellings: the potential to reduce domestic CO<sub>2</sub> emissions

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## **Abstract:**

Historic (i.e. pre-1919) dwellings in the EU account for around 14% of the total stock (21% in the UK) and must therefore contribute significantly to any long-term energy reduction or carbon saving goal. However, the principle of minimal intervention advocated by heritage conservationists is at odds with the fabric-first approach that energy conservationists propound. It is clear, therefore, that a different approach is needed to ensure significant savings are still delivered by the historic stock whilst balancing the need to maintain our built heritage.

In this paper, we raise the question of whether the price of altering the built historic environment is worth the contribution such measures could make to meet the overarching and serious challenge of climate change. We focus the work on the potential for roof mounted Photo Voltaic (PV) installations, by taking a case study approach. The research examines 5 case studies in and around the UNESCO World Heritage city of Bath in the South West of the UK. The generation pattern of the PV systems is compared to electricity demand in the dwelling to assess the potential for maximising the use of PV electricity and minimising domestic CO<sub>2</sub> emissions.

Results indicate that in ordinary energy use patterns, without additional demand management, an average of 56% of electricity generated from a roof mounted PV system is used within the dwelling, reducing CO<sub>2</sub> emissions by an average of 19%. In contrast, typical *actual* savings from changes to the building fabric, which are difficult to implement and often not realised in practice, are around 9%. Results also show that where energy use patterns are arranged to synchronise with PV electricity generation, reductions of up to 23% can be made in CO<sub>2</sub> emissions arising from delivered electricity use.

**Keywords:** Photovoltaic systems, historic dwellings, carbon emissions, occupant behaviour

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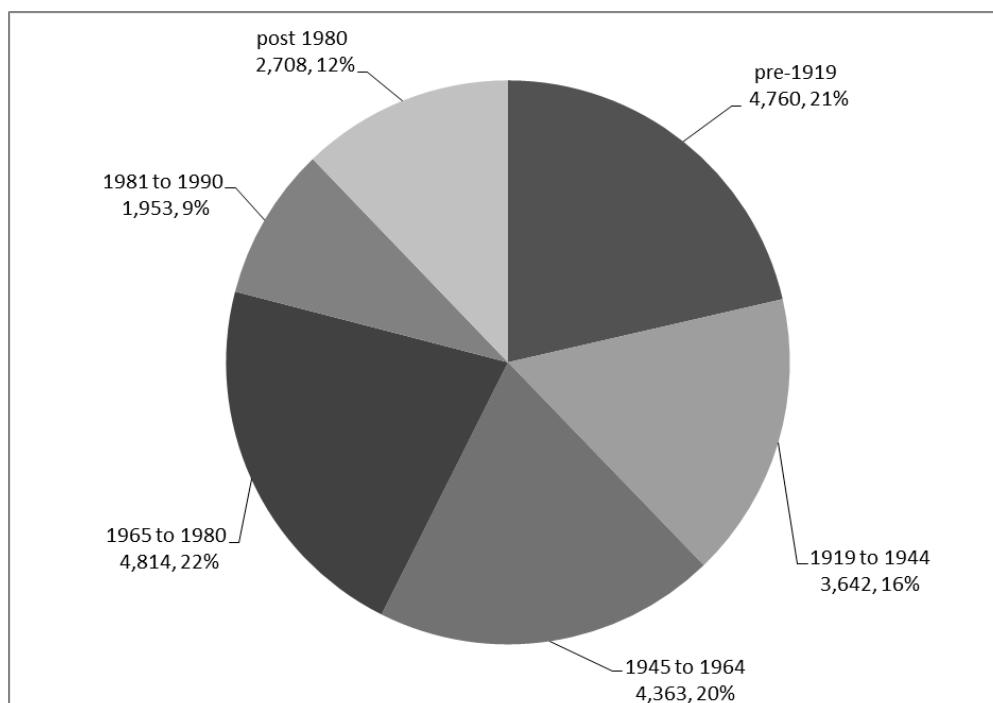
## 1.0 Introduction

Climate change is a key challenge of the 21st Century. Meeting this challenge requires reductions in Greenhouse Gas (GHG) emissions, particularly CO<sub>2</sub>, from all sectors of society. The UK's Climate Change Act mandates a reduction in GHG emissions of 80% by 2050. In addition, as part of its European commitments, the UK is bound to source 15% of its energy from renewable sources by 2020.

Buildings in the UK contribute almost 40% of all emissions [1]; this is higher than the overall contribution of buildings to global emissions at 34.2% (2000 data)<sup>1</sup>. Within the UK, domestic dwellings accounted for 26% of CO<sub>2</sub> emissions in 2010 [2] as a result of operational energy use. As between 70% - 80% of UK dwellings in 2050 have already been built [3], it is clearly necessary to improve the energy efficiency of the existing built stock if carbon reduction targets are to be met.

Figure 1 shows the distribution of dwelling stock by age in England for 2008 [4]. It is evident that a significant proportion of these (4.8 million or 21%) were built before 1919. For the purposes of this study, all pre-1919 dwellings are defined as 'historic' dwellings [5].

These historic buildings have significant cultural and heritage value and the overarching aim of reducing CO<sub>2</sub> emissions demands solutions that are specific, suitable and replicable at district scale to deliver enduring energy efficiency savings and emissions reduction while maintaining their heritage value.



**Figure 1 Number (000s) and percentage of homes by age in 2007**

<sup>1</sup> Table 6, p17 in Price et al, 2006, "Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions", Lawrence Berkeley National Laboratory, LBNL-56144

**Source: English House Condition Survey (EHCS) [4]**

Further, taken together with dwellings built between 1919-1945 (which also have a heritage value), these buildings account for 37% of all dwellings. Whilst built form and age has little effect on electricity use (most heating is provided by gas/oil), the significance of the higher proportion of older dwellings is apparent if their contribution to our built heritage limits the take up of roof mounted PV on grounds of visual aesthetics. This is of importance as the options to reduce CO<sub>2</sub> emissions arising from electricity use in dwellings are limited.

The challenge of reducing CO<sub>2</sub> emissions in existing dwellings is demonstrated by Jenkins *et al.* [6] who modelled an extensive list of retrofit adaptations that could only achieve 52% reduction in CO<sub>2</sub> emissions, but with the inclusion of PV this increased to 75%. This highlights the difficulties in achieving sizeable CO<sub>2</sub> emissions reductions in existing buildings and the potential contribution the adoption of PV systems can make.

In historic buildings achieving such savings is likely to involve fabric and aesthetic alterations. This research aims to evaluate the CO<sub>2</sub> emissions reduction through the adoption of PV arrays in historic buildings under current planning regulations. There is no methodology to balance reduction in emissions against loss of heritage, although carbon emission reductions come at the price of loss of visual aesthetics, perceived or actual. The intention of this paper is to evaluate the benefit of carbon savings thereby quantifying the retrofit adaptation benefit of PV systems in historic buildings.

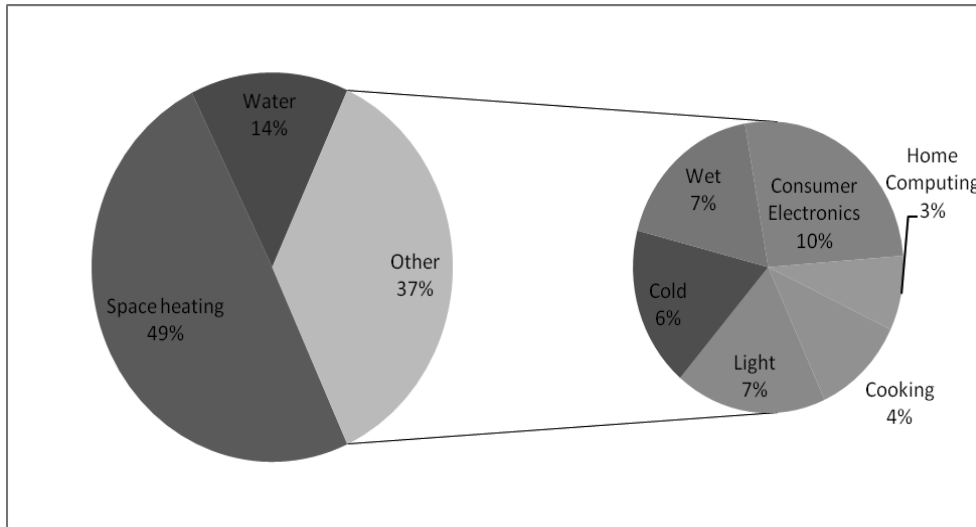
This approach challenges the long held conservation principles [7] of minimal intervention to use less energy, reduce emissions and maintain comfort in buildings by advocating the adoption of effective and durable adaptations.

## **1.1 Domestic Energy Use**

Figure 2 shows that the majority of energy use in the home is for heating and hot water (63%). The options to reduce this demand in historic buildings are varied and on the whole well understood but are not fully implemented for many reasons, including conservation constraints, cost, planning restrictions and the possible risk of loss or decay of building fabric. Current orthodoxy focuses on reducing this demand through improvements to fabric and system efficiency before turning to low and zero carbon technologies (LZC). We argue here, however, that given the contribution of electricity use to overall carbon emissions, LZCs have a role to play, especially for historic building where options for fabric improvements may be somewhat limited.

Although electricity use in dwellings is typically 15% of total energy use [8] it contributes to 37% of the total domestic carbon emissions (UK electricity currently has 2.4 times the carbon factor of gas [9]).



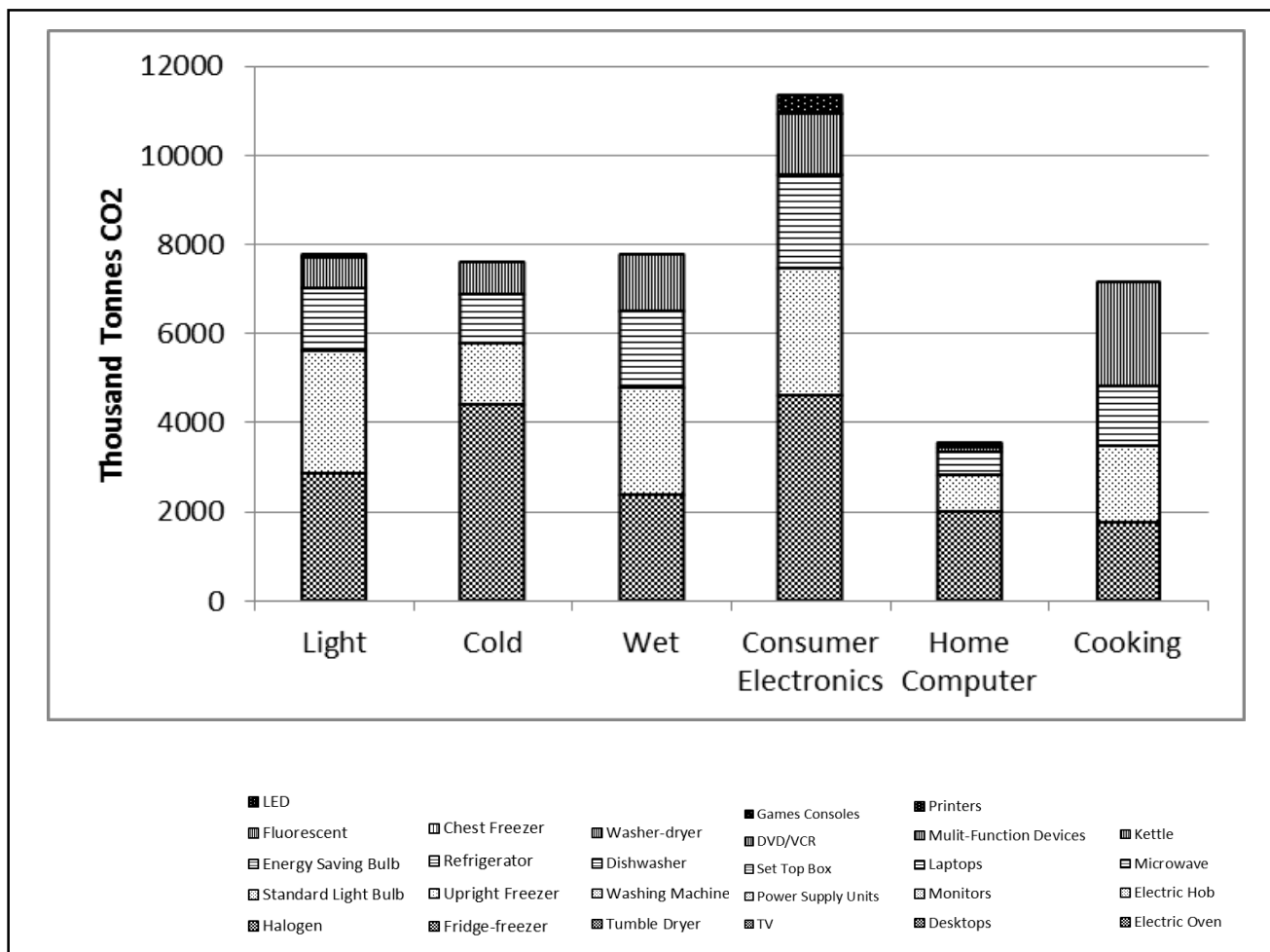


**Figure 2 Domestic CO<sub>2</sub> emissions by source [8]**

This is significant, because unlike heating and hot water the options to reduce CO<sub>2</sub> emissions arising from electricity use are both limited and distinctly different. One possibility is to reduce the carbon factor of delivered electricity; this is beyond the control of householders and is more a function of government energy policy requiring long-term structural changes to supply. Other options are to demand reduction or the adoption of LZC technology.

## 1.2 Domestic Electrical Demand Reduction

The breakdown for domestic electrical use emissions is at Figure 3, this shows there are several areas to focus attention on within the home to reduce CO<sub>2</sub> emissions.



**Figure 3 Breakdown of Domestic Electricity Use 2010 [10]**

One is to reduce lighting demand through increased use of low energy CFL and LED light fittings. Recent regulations [11, 12] have significantly improved uptake but these remain expensive and occupants are not always satisfied by the type of light produced. Similarly, energy efficient choices are now widely available when replacing appliances. However, the most efficient A++ rating appliances currently have limited availability and are generally an expensive alternative to an A rated appliance. Furthermore, household awareness is an issue since only 16% were aware of the energy rating of their new appliance when making a replacement purchase [13], thus illustrating the problem of uptake even if more efficient appliances are on the market. Finally, another option is real-time occupant energy use feedback. The potential impact of monthly feedback on energy use patterns is usually estimated to be 5–10% [14], but it would appear that initial savings cannot be sustained in the medium to long-term [15]; this is an area of on-going research.

Within the home there are also elements of occupant behaviour that can deliver energy savings. Examples are switching off lights/appliances when not in use, avoiding the use of standby mode for audio and television units, as well as avoiding leaving various charging units on while not charging.

### 1.3 Future climate change and cooling loads

There is currently no Government data for UK domestic cooling load use. Figure 3 does not show the demand for summer domestic cooling as this is currently very small compared with overall energy consumption. This will change in coming decades. Peacock *et al.* [16] state that if the behavioural response of UK householders to a warming climate is akin to that of relationships found in the US, the expected domestic cooling season created as a consequence of climate change will see 18% of homes in the South of England having installed domestic air conditioning systems by 2030.

This is likely to adversely affect carbon emissions as cooling will require electricity that currently has a carbon factor 2.4 times greater than gas. One study predicts that an increase in energy consumption due to the growth in active cooling systems in London by 2030 (550,000 homes with air conditioning equipment [18]) may lead to a doubling of CO<sub>2</sub> emissions by 2030 [17]. This does not take into account savings as a result of a reduced heating load which may be as high as 40% for terraced dwellings [19]. Regardless of the overall net demand impact, there is consensus that changing climate will see an increase in domestic cooling demand. In this respect PV output is aligned to cooling demand and can provide low carbon electricity to service this requirement.

### 1.4 PV generation

Another approach to reducing domestic CO<sub>2</sub> emissions is to adopt Photo Voltaic (PV) systems to provide low carbon electricity. This is in line with the current government renewable energy strategy that seeks to increase decentralised micro renewable generation. This approach is supported by Natarajan's and Levermore's [20] view that on-site renewable energy generation will be key to reducing or even balancing emissions through energy export.

This would suggest the onsite generation of electricity is essential to meet future CO<sub>2</sub> emissions reduction targets. For some time there has been growing acceptance that renewable energy technologies can achieve a significant reduction in CO<sub>2</sub> emissions beyond that from the standard energy-efficiency methods [21]. The recent introduction of Feed in Tariffs<sup>2</sup> for micro electricity generation in the UK and the prospect of the same for renewable heat, is likely to increase take up of domestic micro renewable energy generation systems (this has already been observed in the PV market at the time of writing). These tariffs are likely to be at least as beneficial (if not more, as suggested in this paper) in historic buildings as the rest of the housing stock, though there is currently little evidence to measure this effect.

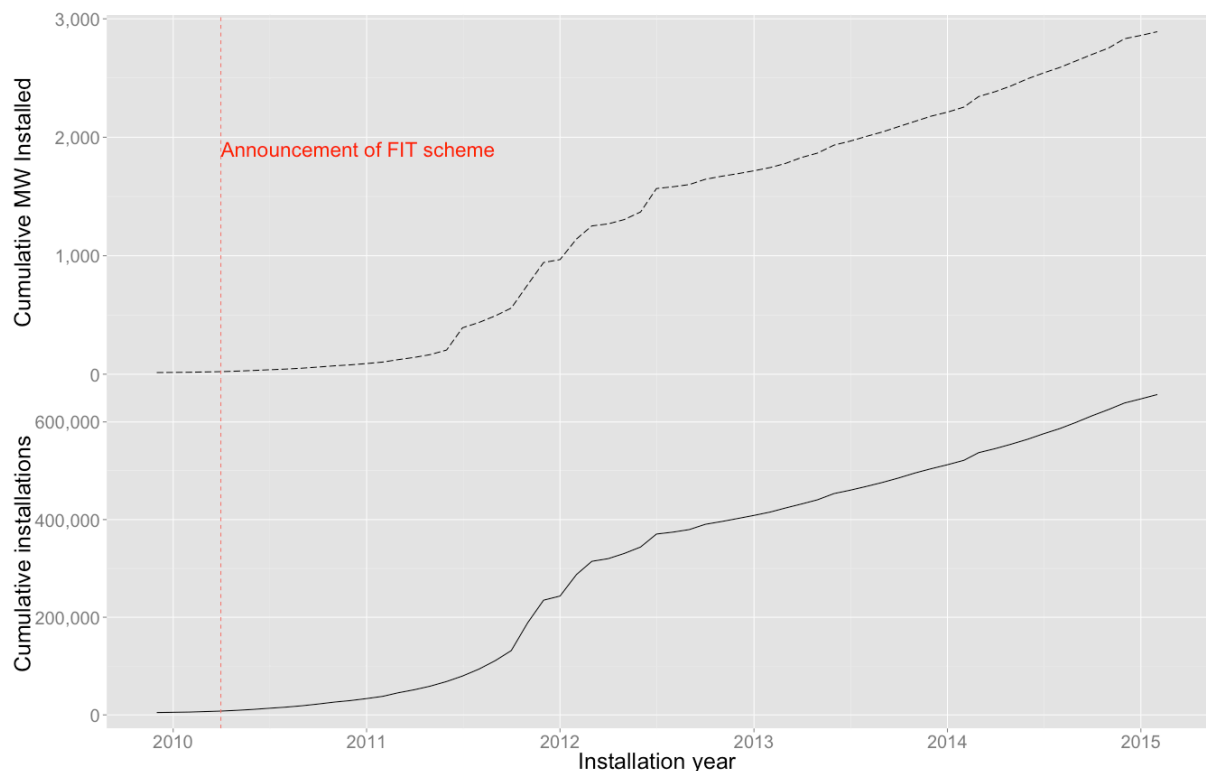
A key issue is that current orthodoxy considers PV as a last option once all other energy efficiency measures have been implemented. Whilst this approach may be prudent with regard to provision of heating and hot water, where improved energy efficiency generally

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<sup>2</sup> A payment made to households or businesses for each kWh of electricity generated through the use of low and zero carbon technologies, including PV arrays. A further payment is available for each kWh of electricity exported to the National Grid.

leads to reduced plant size and therefore lower capital costs. The same cannot be said of PV, which as it affects only emissions from electricity consumption can in fact be sequenced quite separately from adaptations to reduce heat loss from the fabric.

Since the introduction of the FiT in April 2010, as of September 2012 the installed capacity of PV has increased from 7MW to 1.45GW [22], see Figure 4.



**Figure 4 PV Installations in the UK**

Growth in this technology is expected to continue, DECC project delivery of 2.7GWp of PV by 2020 [23]. This paper does not consider the economics of PV. This is primarily because the level of subsidy available to PV is under continual review in the UK and other studies have considered this in detail [24, 25, and 26]. In addition, regardless of the precise nature of any future financial incentive, the 372,391 installations between April 2010 and September 2012 [22], demonstrate that PV installations can be made financially attractive.

From Figure 3 it can be seen that PV has the potential to provide low carbon electricity for wide areas of demand. Given that PV output only occurs during the day, the match between supply and demand is likely to be weak for occupants working away from home, for lighting and cooking and zero for night demand. Whereas there is strong potential to match supply and demand for daytime activities including Cold, Wet and elements of Consumer Electronics and base load electricity use. This demand match is further enhanced where the home is occupied during the day (e.g. retired occupants, home workers, unemployed and students).

## 2.0 Methodology

This paper sets out to evaluate the carbon reduction potential of PV technology in the scenario of historic buildings. The methodology presented will evaluate the benefit of PV generated electricity by establishing and comparing the pattern of PV generation and domestic electricity demand.

The main considered elements were:

- Establish typical dwelling daily energy usage pattern
- Assess PV installation output
- Correlate PV output with daily electricity demand pattern
- Determine how much of PV electricity generated can be used
- Ascertain CO<sub>2</sub> emissions reduction in the dwelling

Five historic dwellings with a PV system installed were monitored for annual electricity generation and export. In four dwellings, monthly generation totals were recorded and in the fifth output was recorded at 1-minute intervals using a Sunny Webbox [27].

Establishing a pattern of daily electrical consumption was challenging. Apart from aggregated and averaged national statistics, demand profiles are available [29]. But there are questions as to how representative they would be of the case studies. It was therefore decided to measure actual electricity demand to establish a representative profile.

In a subset of these 5 dwellings, daily electricity use was measured in two dwellings at 30 second intervals using an Elcomponent energy data logger [27] over a 6 month period from April–September 2011 (see Section 3.2).

To arrive at the carbon emission reduction a grid carbon factor of 0.5246 kg CO<sub>2</sub>/kWh was used [9]. A carbon factor of 0.095 kg CO<sub>2</sub>/kWh was used for PV generated electricity [30], from the data presented this is mid range for domestic PV mono-crystalline in the UK (0.075-0.116 kg CO<sub>2</sub>/kWh). There is little research data currently available on carbon factors for domestic generated PV electricity in the UK. Even at upper limits from recent research domestic PV has a carbon factor considerably less than delivered grid electricity.

## 3.0 Results

### 3.1 Case Studies

Five case studies in and around Bath in the South West of the UK were examined, see Figure 5 for installations. They were a mix of Monocrystalline and Polycrystalline silicon photovoltaic panels with a rated efficiency of between 13.5- 14.1%.



Case Study 1    1.85  
KWp



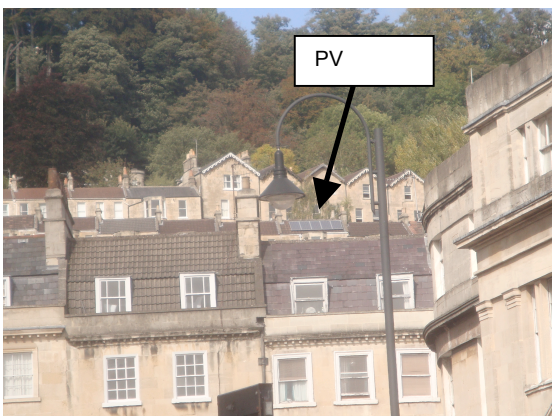
Case Study 2    2.6  
KWp



Case Study 4    3.3 KWp  
Rear, on Outbuildings



Case Study 5    1.85  
KWp  
Central Valley Only



Case Study 3    2.0 KWp  
Central Valley and Rear Elevation

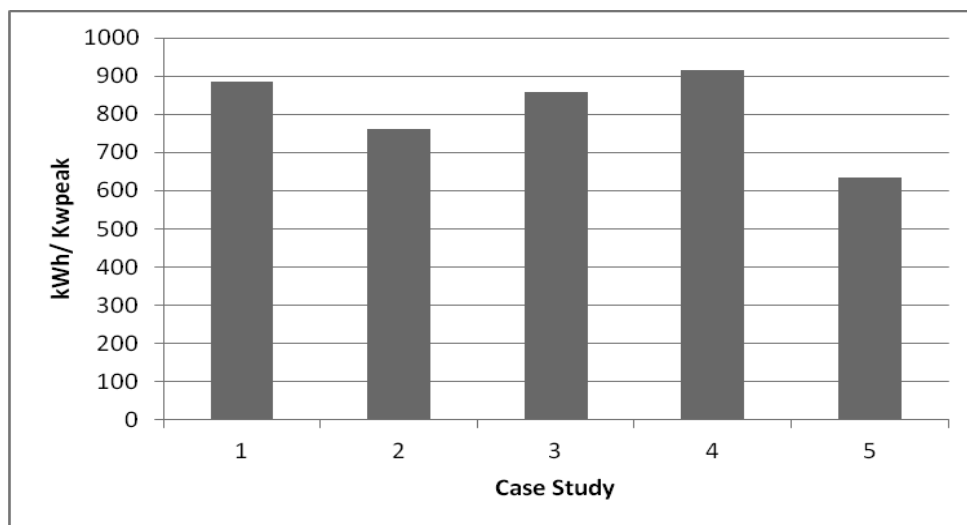
**Figure 5 Case Studies**

Table 1 shows data from the five case study buildings located in and around Bath, UK.

**Table 1: Case study data**

Case Study	1	2	3	4	5
Age(yrs)	215	261	205	218	260
Typology	Semi-Detached	Detached	Terrace	Terrace	Terrace
Status	Conservation Area	None	Conservation Area	Grade II Listed	Grade II Listed
Floor Area m <sup>2</sup>	168	177	160	175	250
Annual kWh used	3462	4323	4526	3807	4388
Annual CO <sub>2</sub> Kg	1869	2334	2444	2056	2370
Electricity kWh/m <sup>2</sup>	20.6	24.4	28.3	21.8	17.6
Installed kWp	1.85	2.6	2.0	3.3	1.85
Rated efficiency	13.9 %	13.5 %	13.7 %	14.1%	13.7%
Generated kWh/yr	1640	1977	1715	3019	1173
kWh/kWp	886	760	858	915	634
Used PV kWh	736	996	1150	705	725
% PV gen kWh used	45%	50%	67%	23%	62%
Exported kWh	904	981	565	2314	448
Offset CO <sub>2</sub> kg/yr from used PV electricity	361	488	515	345	355
% total CO <sub>2</sub> saved	19%	21%	21%	17%	15%

An important indicator of a PV installations performance is the kWh generated per kW peak installed (kWp); this gives an indication of the real performance taking into account location, installation, shading and insolation. Figure 6 shows that in the case studies this varies from 634 – 915 kWh/kWp. Interestingly, all but the lowest output were in line with installers' estimates. The lowest system output was attributable to shading from a large tree and a high ridgeline in close proximity.



**Figure 6 kWh/kWp output**

The difference is explained by variations in orientation, shading (from trees, buildings and chimneys) and system losses. The average performance was 811 kWh/kWp, this provides a useful benchmark when considering the retrofit benefits of PV systems (for this location), which would be independent of dwelling age.

Table 1 shows that there is considerable variation in the amount of PV generated electricity used within each dwelling, ranging from 23-67%. This factor is important when evaluating the net reduction in CO<sub>2</sub> emissions for each dwelling, as it has a corresponding effect on CO<sub>2</sub> emissions reduction by reducing grid-imported electricity. Ignoring the lowest figure (case study 4), which was due to the property having a large 3.3 kWp system (on an out building), the average was 56% of PV generated electricity used within the home, which is slightly higher than the 50% assumed in FiT calculations. This raises the question of how much further use could be made of PV generated electricity to reduce a dwelling's emissions rather than simply exporting excess to the grid. This will be explored further in the discussion section.

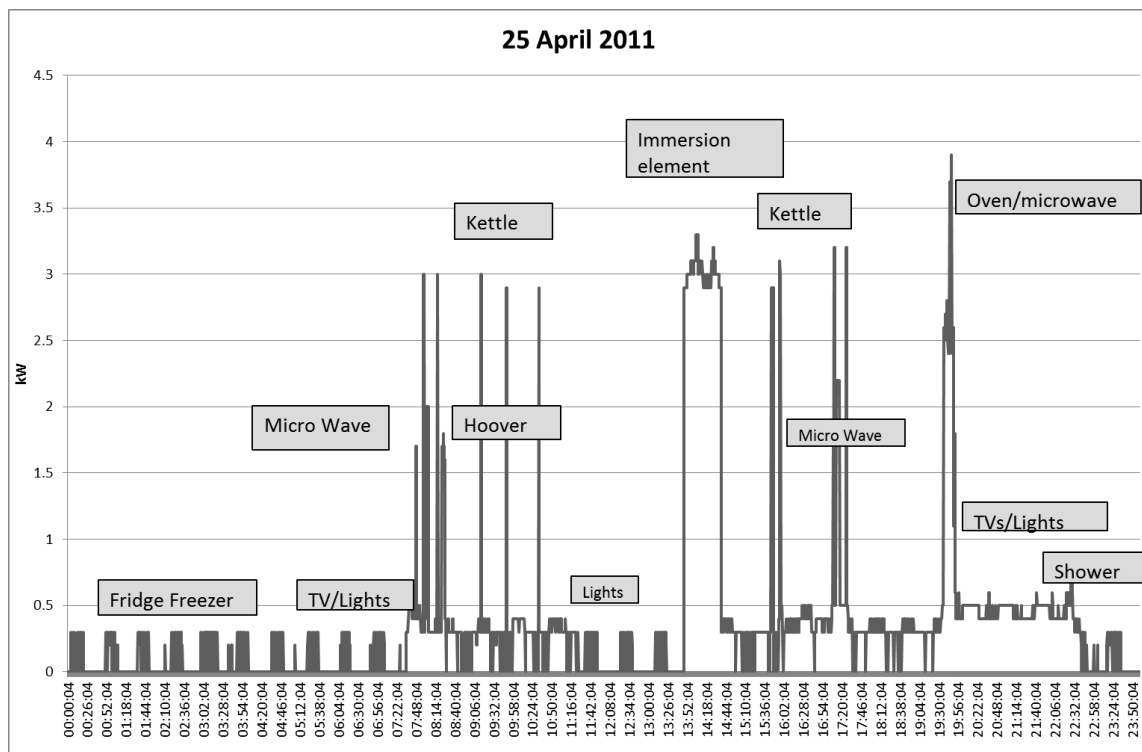
### 3.2 Daily electricity demand

Richardson *et al.* [29] recognise that the pattern of electricity use in an individual domestic dwelling is highly dependent upon the activities of the occupants and their associated use of



electrical appliances. In order to consider alignment of PV electricity production to dwelling electricity consumption energy use patterns were measured for Case Studies 1 and 5.

Figure 7 shows the daily pattern of electricity use in Case Study 1 for normal occupation, this is for occupancy of 2 adults working away from home. In this graph the electric immersion heater was switched on, although normally the gas boiler was used to provide hot water, this was initiated in order to explore matching electricity demand to PV output.

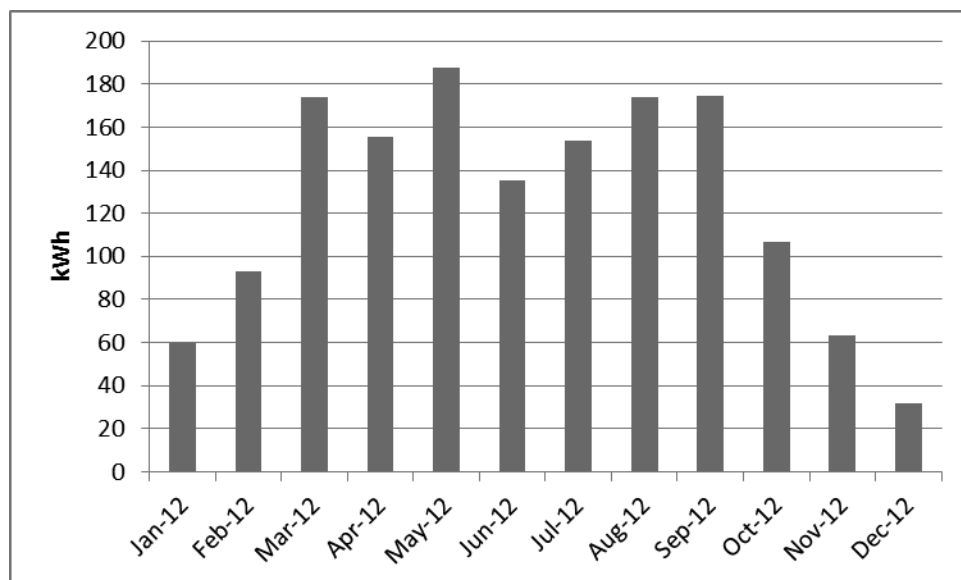


**Figure 7 Electricity energy demand pattern, Case Study 1**

In particular, it shows a peak base load at approximately 350W, this comprises a fridge/freezer, telephone base set, smoke alarms, clock radios, microwave display, toothbrush charger, boiler controls and a timer switch and satellite box standby. This compares favourably to the Domestic Energy Demand Model produced by Richardson *et al.* [24], although this model produces a slightly lower peak base load of 200 watts.

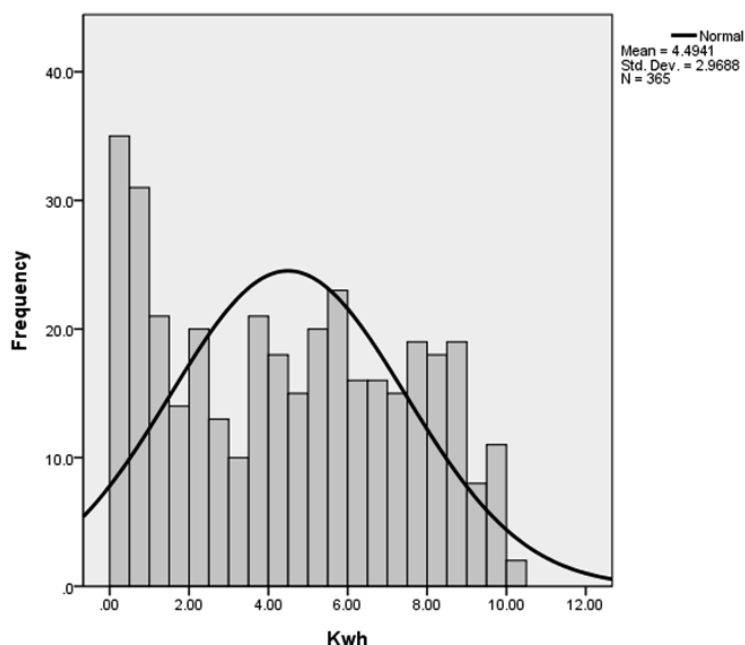
### 3.3 PV System output

PV output from case study 1 was measured from January 2012 to December 2012; the PV system output is at Figure 8.



**Figure 8 Case study 1, PV output 2012**

In order to analyse the match between domestic electricity demand and PV output a histogram of daily PV generated electricity was generated (Figure 9). This shows an average generation of 4.49 kWh/day for the year 2012.

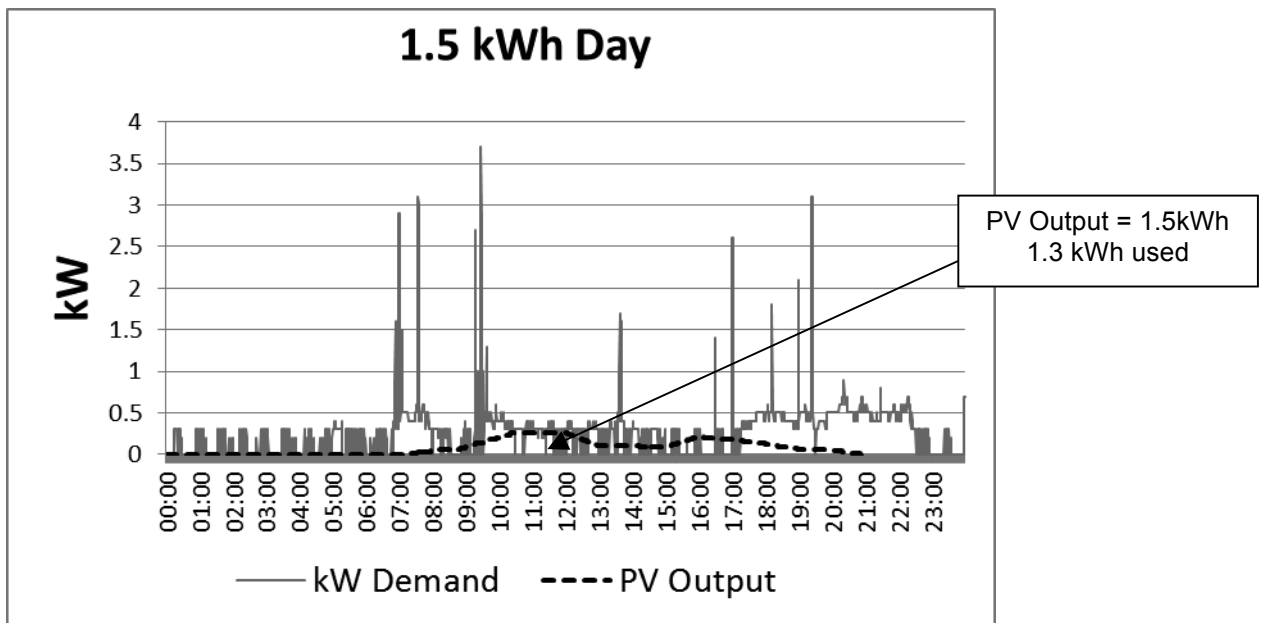


**Figure 9 Histogram daily PV generation Case Study 1**

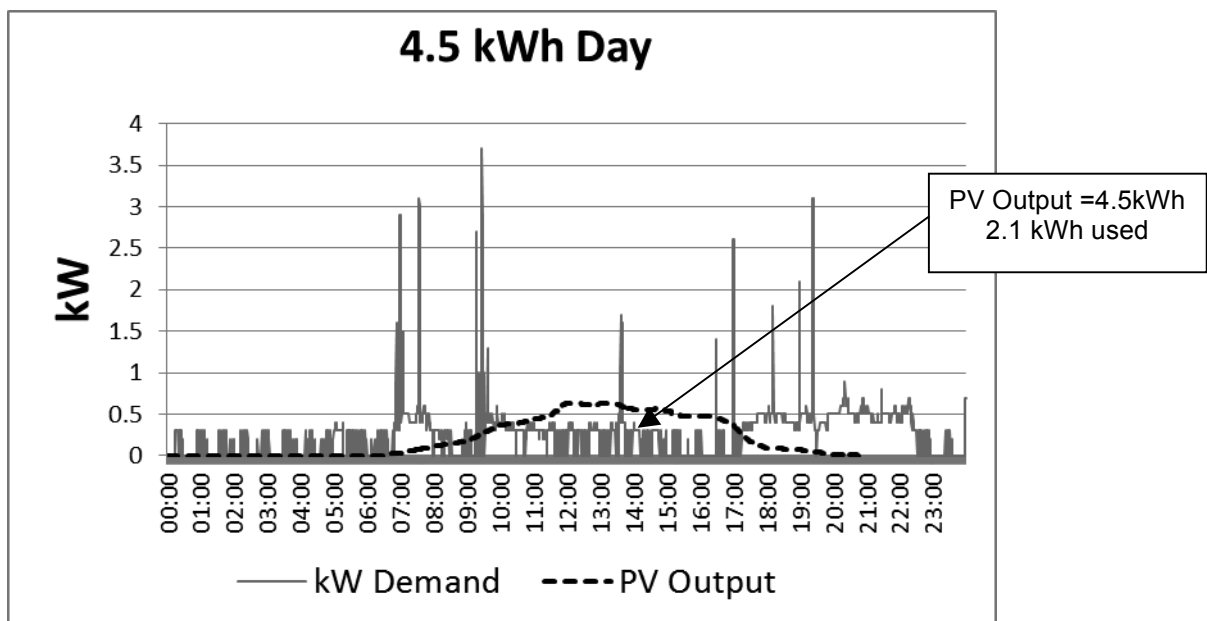
As the contribution PV generation makes to the dwelling CO<sub>2</sub> emissions is dependent on the amount of insolation, the data collected was used to establish three typical PV days using the mean and upper and lower quartiles from Figure 9:

- Lower quartile PV day of 1.5 kWh/day
- Mean output PV day of 4.5 kWh/day
- Upper quartile PV day of 7.5 kWh/day

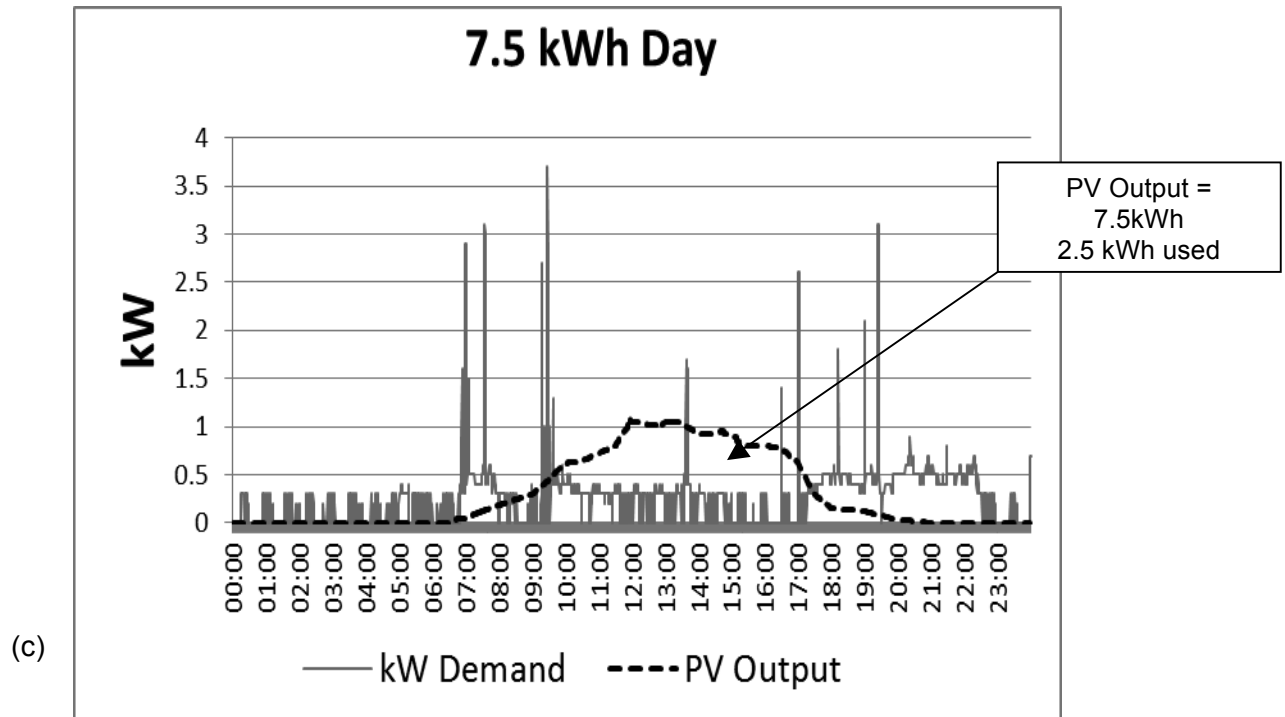
These PV outputs were then compared to daily patterns of electricity demand (no electric hot water immersion element). This showed that for weekday occupancy, regardless of the PV output above the baseload of 2.3 kWh/day, there is little variation in the amount of PV generated electricity used within the dwelling (Figure 10). Note that electricity is exported when the PV output line goes above the energy demand line. This could be viewed as a missed opportunity to reduce dwelling carbon emissions.



(a)

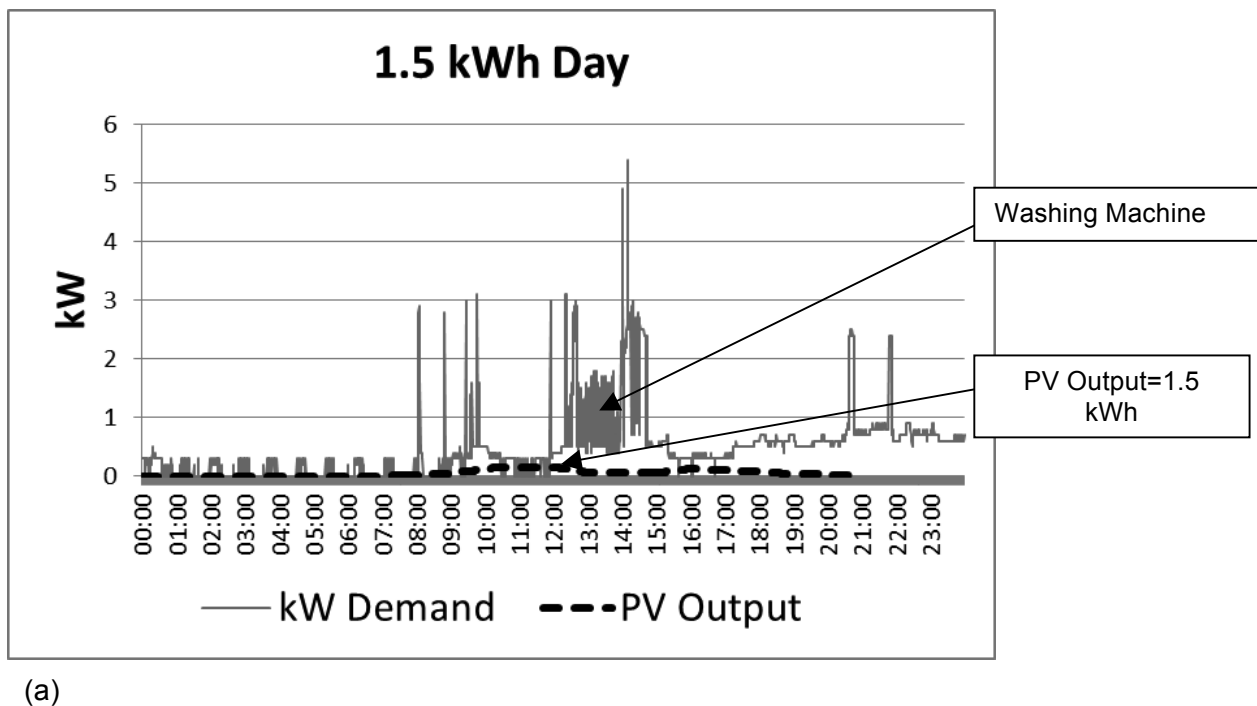


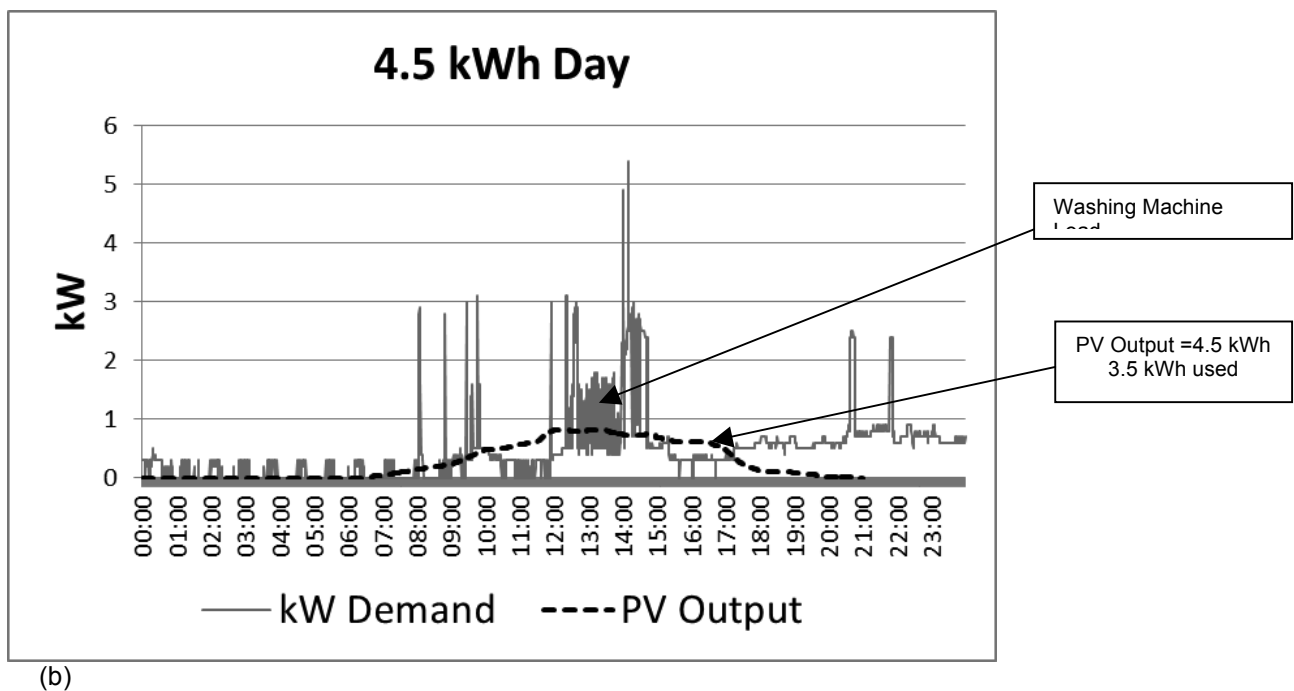
(b)



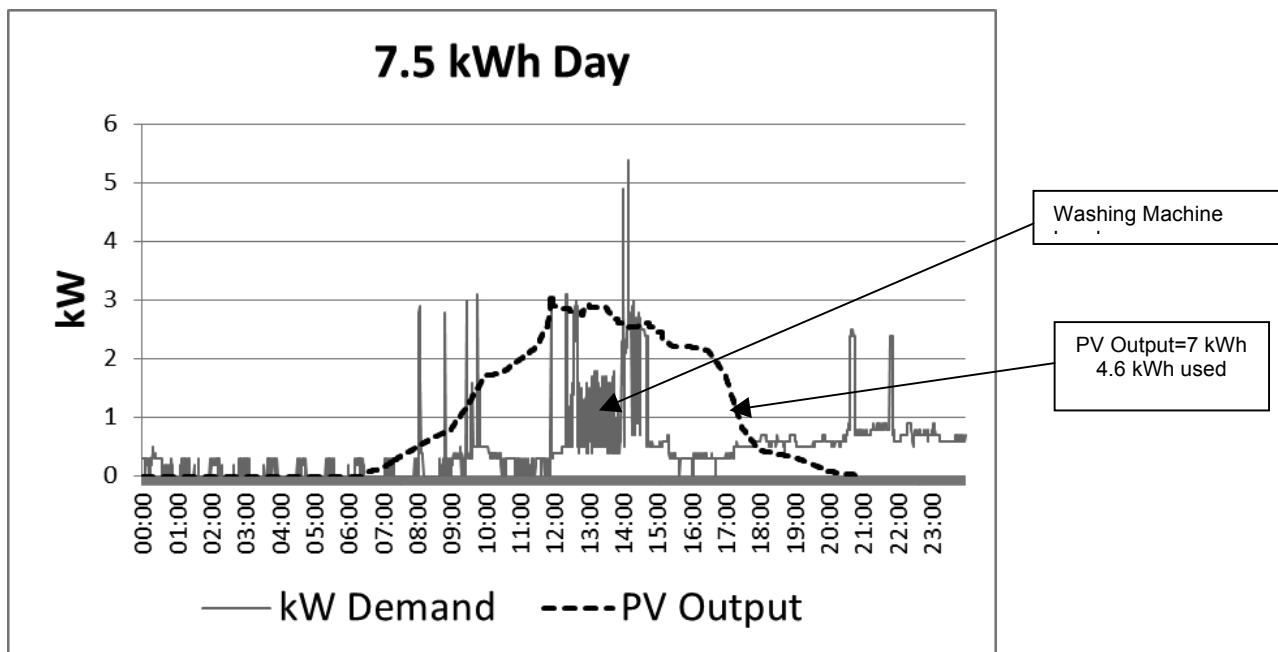
**Figure 10 Domestic Electrical Demand and PV Generation split by days of (a) low (1.5 kWh) (b) medium (4.5 kWh) and (c) high (7.5 kWh) PV output.**

The use of a washing machine increases the use of PV generated electricity as its power rating is closer to the PV systems output on average and high output days, see Figure 11.





(b)

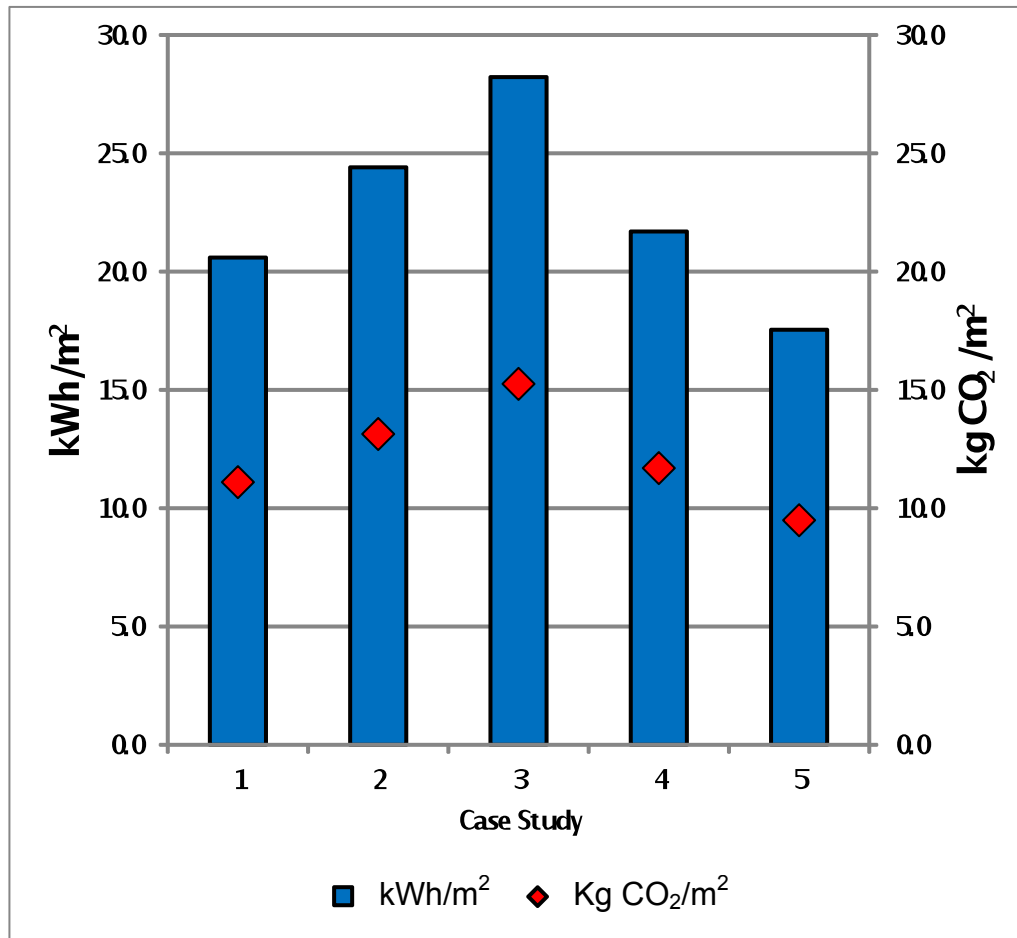


(c)

**Figure 11** PV output v washing machine electricity demand split by days of (a) low (1.5 kWh) (b) medium (4.5 kWh) and (c) high (7 kWh) PV output.

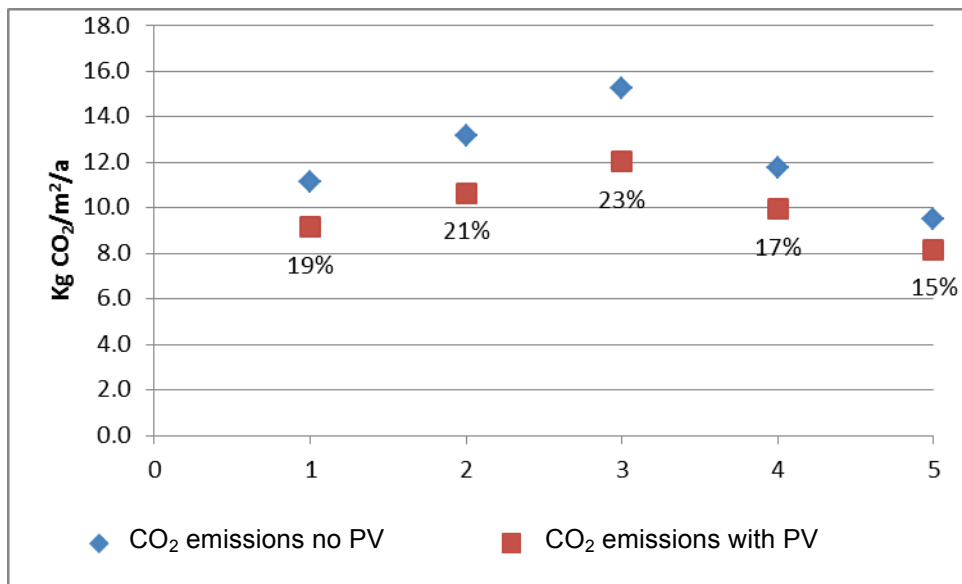
### 3.4 CO<sub>2</sub> Emissions

Annual CO<sub>2</sub> emissions from delivered electricity use were established from utility bills, these were normalised to internal floor area (Figure 12).



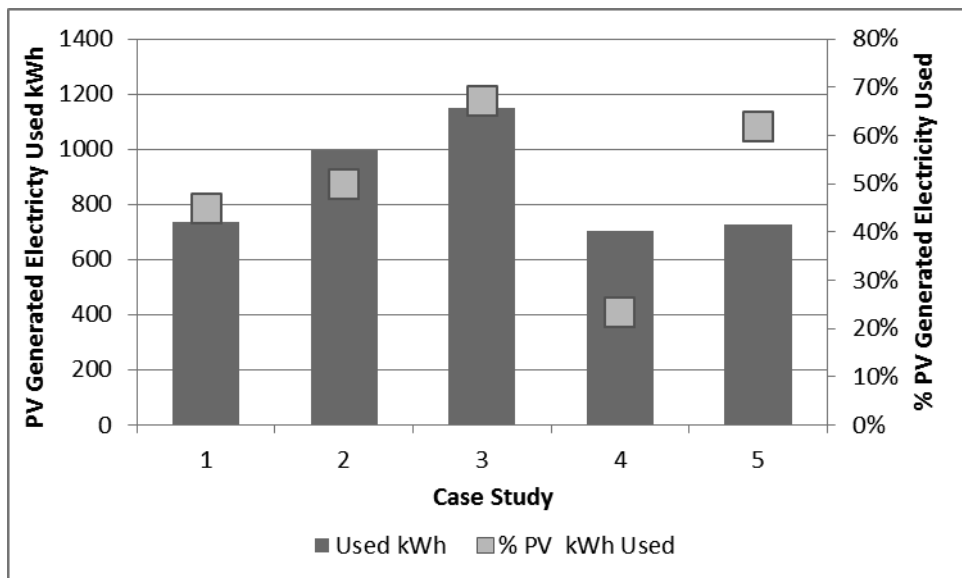
**Figure 12** CO<sub>2</sub> emissions from delivered electricity use (no PV)

The effect of savings from the generated PV electricity on annual electricity use is shown at Figure 13, this shows a reduction in CO<sub>2</sub> emissions of between 15 – 23% (average 19%).



**Figure 13** CO<sub>2</sub> emissions from delivered electricity use with and without PV.  
Percentages show reductions obtained with PV compared to the no PV case.

The potential to reduce CO<sub>2</sub> emissions is dependent on the portion of PV generated electricity used. This also has an impact on repayment costs as a displaced unit of imported electricity is currently worth 4 times more than an exported unit. Figure 14 shows the amount of PV electricity used which varied from 23-67%.

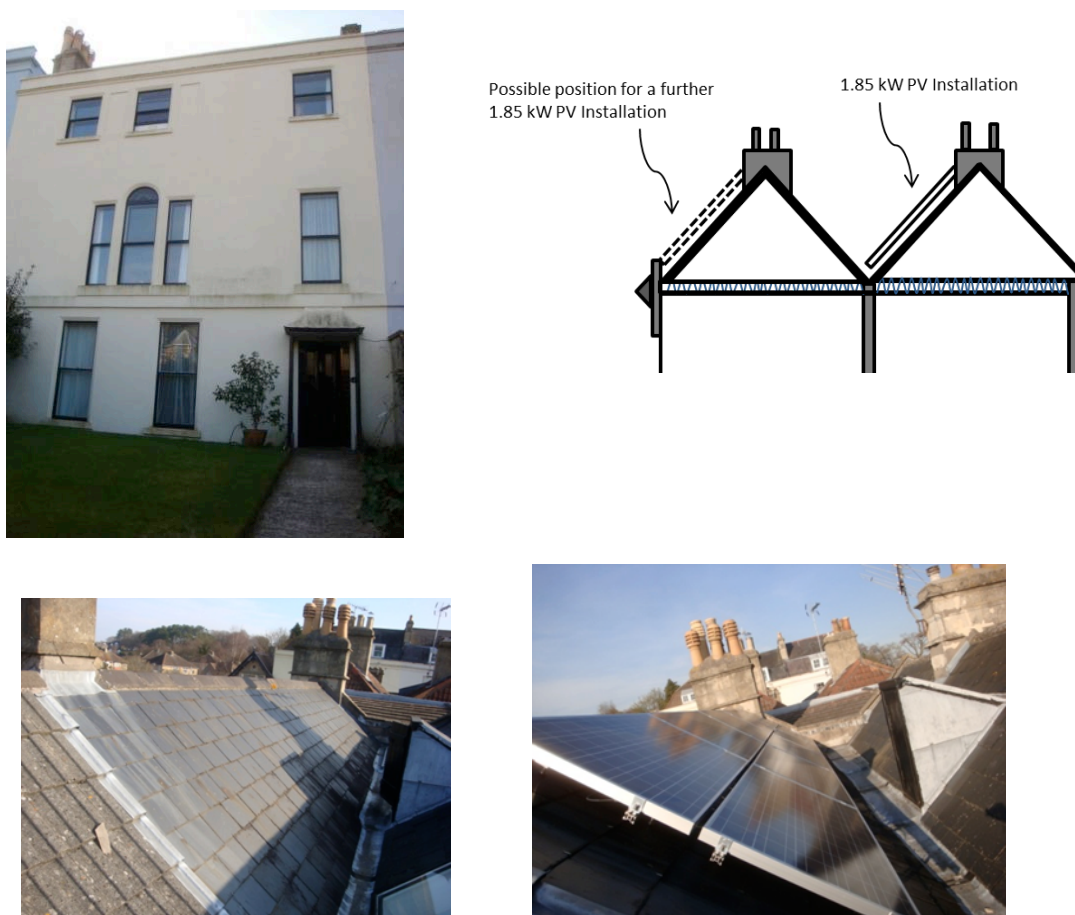


**Figure 14** Amount and Percentage of PV generated electricity Used

The variation in PV generated electricity used is attributable to occupant attitude and behaviour, patterns of occupancy and the size of the PV system. A post survey interview revealed that the occupants in case studies 3 and 5 were particularly keen to reduce their CO<sub>2</sub> emissions and made a conscious effort to use appliances on good PV (sunny) days. Actions included deliberately timing the use of appliances, particularly washing machines, dishwashers and vacuum cleaners, with high PV output, to avoid importing electricity at a higher cost.

An interesting comment was made by Case study 5 who said that they would have increased the amount of PV used if there was an automatic means to activate devices to suit PV output, “rather than waiting for the sun to shine before switching on the washing machine”.

Although case study 5 used 61% of generated PV electricity it reduced its CO<sub>2</sub> emissions by the lowest amount, 15%. This is due to: (i) reduced output (kWh/KWp) as planning permission was only granted for a PV installation in the central valley of the roof and (ii) limitations in the size of the PV system due to its Grade II listed status, see Figure 15.



**Figure 15 Case Study 5**

So although there was potential for a 3.7 kW system by using both south facing roof elevations, only a 1.85kW system received planning permission. If a 3.7 kW system had



been installed, increased PV generated electricity would result in increased CO<sub>2</sub> emissions reduction, moving from 15% to at least 21%.

This can be supported by Case Study 3 which had a similar roof construction but although in a nearby conservation area was not a Listed Building; consequently it installed a 2.0 kW PV system utilising both south facing roof sections, achieving a 21% reduction in electricity CO<sub>2</sub> emissions.

## 4.0 Discussion

Is PV just a new aesthetic? Historic buildings have already changed much over time; examples are the use of gas for lighting followed by electrification, the introduction of bathrooms and central heating, conversion to smaller units and the use of previous below ground storage and roof areas for accommodation. This suggests further change to reduce emissions may, with time, become just as accepted.

Historically the driving force for altering our historic buildings was more one of convenience and comfort. The difference today is that we now need to reduce the CO<sub>2</sub> emitted from our homes; this is a new approach and is to some extent out of line with cultural norms with regard to our built heritage. Today's new low carbon paradigm means that we have to retrofit our existing housing stock, including historic buildings.

The current orthodoxy for improving energy efficiency in buildings centres on reducing the heating load, and only when this is achieved does it turn to dealing with the approximate 35% contribution electricity use makes to CO<sub>2</sub> emissions. Historic buildings may require a different approach. The introduction of PV in this building typology, though currently recommended as one of the last retrofit measures, can lead to reductions in CO<sub>2</sub> emissions through using considerably less delivered electricity. When primary energy production losses are considered the benefits increase.

As a result it may be that we are approaching a turning point where marginal aesthetic or traditional reasoning may have to give way to environmental imperatives. Perhaps we should consider that *"we may have to be prepared for visually intrusive measures on much loved buildings"* [30]. This view may gather momentum because the options to improve energy efficiency in historic buildings are limited, even more so when dealing with electricity derived CO<sub>2</sub> emissions.

As historic buildings have withstood many changes in the past, is the introduction of renewable energy technologies really such a problem? They are after all, fully demountable and leave the fabric intact. One argument against them is that these interventions are simply a question of glamour because the really effective measures (insulation, improved energy efficiency and draught proofing) are unattractive, and from observation, often ignored. Whilst this may well be the case, none of these measures would have a noticeable effect on emissions arising from electricity use.

Apart from the status of these dwellings there were few fabric differences between them that would affect the adoption of PV. The status of the historic building, in particular if it is a

listed Dwelling, can prevent or limit the potential for the dwelling to reduce its carbon emissions through the adoption of PV.

These findings regarding carbon emissions reduction arising from delivered electricity may be just as applicable to more modern dwellings, but unlike historic buildings they can implement a fabric first approach to reduce carbon emissions. Further work is required to assess the potential contribution Historic buildings can make, are the roofs of such buildings more suitable, through either total available surface area or orientation. Is there a correlation between the occupants of historic buildings and their pattern of electricity use that aligns with PV output.

This research also raises the following questions and issues about the introduction of the PV regardless of building typology:

1. Can occupants be better informed at the time of PV installation (or when purchasing a dwelling with PV installed) to make optimal use of PV generated electricity?
2. How can the demand of domestic appliances be automatically controlled to make use of PV generated electricity; this is effectively the application of “load matching” or “demand shifting” within the home.
3. Is it feasible to use/store surplus PV electricity production to provide hot water or water pre heating? This requires further research as there are a number of factors to consider such as the efficiency of the boiler providing hot water, the immersion heater element power rating, the time of day the water is heated/pre heated, what other loads are present, controls for initiating immersion element to match PV output and what level of PV output makes this viable.
4. Does it matter if PV generated electricity is exported when not required and imported via the grid at a later point? It could be argued that this simply offsets electricity imported at times when PV generation does not meet demand. But when counting carbon and establishing annual domestic emissions, imported electricity will have a carbon factor some 10 times greater than PV generated electricity. Further data is required on the exact carbon factor of domestic PV generated electricity in order to predict accurately full life cycle carbon reduction benefits.

## 5.0 Conclusions

The study looked at only 5 case studies over a 12-month period. Further continued observations are required to explore the potential of domestic PV generation to reduce domestic CO<sub>2</sub> emissions. The lifetime of PV panels is at least 20 years; even with degradation at 1% year, their future performance can be reasonably predicted. What is less clear is the likely future carbon factor of grid electricity and the bearing this will have on domestic PV to offset emissions.

It has been shown that in ordinary energy use patterns, without demand management or alignment, an average of 56% of electricity generated from a roof mounted PV system is used within the dwelling, reducing CO<sub>2</sub> emissions by an average of 19%. In the overarching aim to tackle climate change this is a sizeable reduction. For comparison, we have shown previously that typical *projected* savings from changes to the building fabric for similar buildings are around 30% [31].

The 19% reduction observed here becomes particularly salient given the contrasting nature of obtainable (i.e. in-practice) savings from PV compared to fabric-based solutions. Savings from PV are constrained primarily through the availability of adequate roof space and the significant cost of the panels and installation. Fabric based approaches are constrained by the ability to access and carry out the works, planning restrictions and importantly: the quality of the works carried out. Research into the energy performance gap has shown that inadequate installer training, poor detailing and workmanship, complexity of on-site works etc. significantly impact the ability to deliver projected savings [32]. Any savings obtained thus are also subject to comfort take-back, which may be significant in older properties. Research has shown that only around 30% of the expected savings using such measures may be realised due to the combined effect of issues related to the performance gap and comfort take-back [33]. Applying this to our expected saving of 30%, actual savings are likely to be only around 9%. Considering the significant challenges in realising changes to fabric in historic buildings, the 19% reduction in CO<sub>2</sub> emissions reported here from relatively straightforward PV installation, even factoring in its higher cost, would appear to be highly attractive.

Finally, the reduction of 19% can be improved upon with demand management; the 67% use of generated PV electricity reported in this paper was achieved without any installed demand management measures, suggesting this figure could be increased. This shows that where energy use patterns are arranged to synchronise with PV electricity generation and where the installation of PV systems are permitted to make use of available roof space, regardless of its heritage value, reductions of at least 23% can be made in CO<sub>2</sub> emissions arising from electricity use.

Restricting the installation of PV modules due a dwellings heritage status misses an opportunity to reduce carbon emissions in dwellings that cannot always follow the fabric first approach more often adopted in more recent dwellings.

The demanding target of 80% reduction in CO<sub>2</sub> emission levels by 2050 suggests that this cannot be achieved without involving historic dwellings. This is a challenge, not only because of the high number of dwellings involved, but also because of aesthetic/fabric constraints. Consequently, and in response to the overarching need to tackle climate change, all low carbon options should be exploited, particularly as the adoption of PV in historic buildings shows the potential to significantly reduce dwelling electricity CO<sub>2</sub> emissions. The challenge now is how to bring together the conservation of heritage and conservation of energy to reduce CO<sub>2</sub> emissions

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